



Evidence that hurricanes are getting stronger

Kerry Emanuel^{a,1}

On average, over the past 50 y, tropical cyclones have killed 10,000 people and incurred damages of \$15 billion annually around the globe, while, over this interval, the population exposed to tropical cyclone hazards tripled, owing to migration into coastal areas (1). Theoretical work published more than 30 y ago predicted that greenhouse gas-induced climate change would increase the thermodynamic upper bound on tropical cyclone winds and thereby lead to a higher frequency of intense storms. The high toll of tropical cyclones and the human migration to coastal regions make it vital to find out whether the predicted increase of intense cyclones is actually occurring. But the paucity of intense storms, coupled with poor data quality, has made it difficult to detect theoretically predicted trends in the tropical cyclone record. In PNAS, Kossin et al. (2) attack this problem by analyzing satellite imagery over the period 1979–2017 and show a statistically significant upward trend in the global proportion of intense tropical cyclones.

Tropical cyclone intensity is limited by the rate at which heat can be extracted from the ocean, the rate at which the energy of the winds is dissipated, and the thermodynamic efficiency of the process, which depends on difference of temperature across the troposphere (3). The limiting surface wind speed is referred to as the potential intensity, and increasing greenhouse gases lead to an increase in this limit (4). It is straightforward to calculate the potential intensity from gridded climatological data, and, as shown in Fig. 1, such calculations show that the thermodynamic limit has indeed been increasing in regions prone to tropical cyclones.

Although increasing potential intensity does not necessarily imply increasing overall frequency of tropical cyclones, it does imply an increase in the incidence of the most intense storms. It is these intense tropical cyclones that cause the great majority of damage and loss of life (5). Thus, changes in overall tropical cyclone frequency, which is dominated by weak storms that usually cause little damage, may not be so relevant as changes in the incidence of strong storms.

Detecting any trends, natural or otherwise, in existing records of tropical cyclones has proven very difficult. Surface wind speeds have been estimated fairly accurately by reconnaissance aircraft for many decades, but only North Atlantic tropical cyclones are routinely surveilled by aircraft, and then only if they pose a threat to inhabited land. Because North Atlantic storms only account for about 12% of global tropical cyclones, the vast majority are observed only from space until and unless they make landfall.

Satellites are very good platforms for detecting tropical cyclones, and it is believed that virtually every tropical cyclone of hurricane intensity (wind speeds exceeding $33 \text{ m}\cdot\text{s}^{-1}$) has been detected since about 1980. But it has proven far more difficult to estimate tropical cyclone surface winds from space. Satellite-borne scatterometers transmit pulses of microwave radiation that backscatter off capillary waves on the sea surface, giving accurate estimates of wind speed and direction, but the frequencies used are also strongly absorbed by raindrops, rendering the technique virtually useless in the high-wind cores of tropical cyclones, which are also regions of very heavy rainfall.

Meteorologists therefore rely on pattern-matching algorithms applied to satellite visible and infrared imagery to estimate hurricane intensity, as usually measured by surface wind speed. These algorithms are collectively referred to as the Dvorak Technique (6). The technique itself and the satellite imagery on which it is based have steadily improved over the years, which has improved intensity estimates and thereby permitted better forecasts of tropical cyclone wind speeds. But this same trend complicates attempts to detect intensity trends, because the more advanced technique and ever better spatial resolution of the satellite imagery enables detection of stronger events. In earlier times, the intensities of the stronger storms were underestimated by the Dvorak Technique, mostly because of the limited spatial resolution of the satellite-borne instruments.

In PNAS, Kossin et al. (2) compensate for the improving instrumentation by systematically degrading

^aLorenz Center, Massachusetts Institute of Technology, Cambridge, MA 02139

Author contributions: K.E. analyzed data and wrote the paper.

The author declares no competing interest.

Published under the [PNAS license](#).

See companion article, "Global increase in major tropical cyclone exceedance probability over the past four decades," [10.1073/pnas.1920849117](https://doi.org/10.1073/pnas.1920849117).

¹Email: emanuel@mit.edu.

First published May 29, 2020.

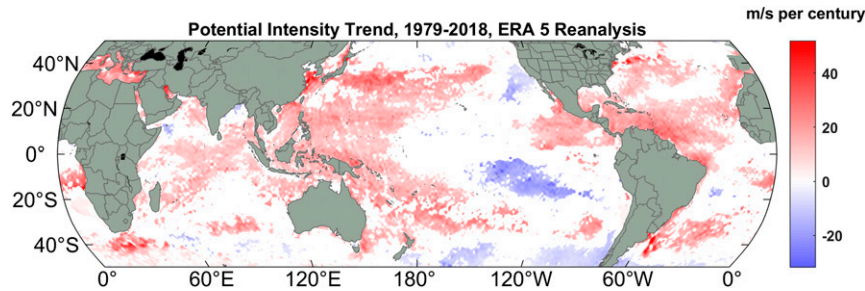


Fig. 1. Linear trend in potential intensity (in meters per second per century, color scale at right) from 1979 to 2018, calculated from European Centre for Medium-Range Weather Forecasts Reanalysis 5 (ERA 5) dataset. Trends are only displayed where their *P* values are 0.2 or less.

the resolution of the more recent imagery to match that of the older satellite instruments, creating a homogenous record. As the authors note, degrading the more recent imagery can artificially damp any real upward trends, so that any detected upward trends can be regarded as lower bounds on the real rates of increase.

In their previous work (7), the authors applied this method to satellite measurements from 1982 to 2009, and, although they documented global upward trends in intensity, these trends did not pass conventional tests for statistical significance. In this update, the authors extend the record to the 39-y period 1979–2017 and here find statistically significant upward trends in the exceedance probabilities of major tropical cyclones (storms whose lifetime maximum surface winds exceed $50 \text{ m}\cdot\text{s}^{-1}$) and in the proportion of all detected tropical cyclones that are classified as major storms. Specifically, their results indicate a global increase of about 8% per decade of the probability that a given tropical cyclone will become a major storm, with 95% confidence bounds of 2% and 15%.

We can compare this number to expectations based on the observed rise of potential intensity in regions prone to tropical cyclones. Based on Fig. 1 (also see ref. 7), this amounts to roughly $1.5 \text{ m}\cdot\text{s}^{-1}\cdot\text{decade}^{-1}$ or, given a mean tropical potential intensity of around $70 \text{ m}\cdot\text{s}^{-1}$, about $2\% \text{ decade}^{-1}$. The observed cumulative frequency distribution of tropical cyclone intensities has a

slope of around -3.7% per 1% increase in potential intensity near the transition to major tropical cyclone intensity (see figure 7a of ref. 8). This would yield an increase in the probability of encountering major tropical cyclone wind speeds of about 7.5% per decade, in good agreement with the updated results of Kossin et al. (2).

The verification of a decades-old prediction that tropical cyclones would become more intense as a result of global warming has far-reaching implications for society. The increase in wind speed is compounded by the fact that the two most destructive aspects of tropical cyclones—storm surges and rain—also tend to increase with storm intensity. Moreover, the increase in sea level brought about by global warming increases flooding from storm surges even in the absence of changes in storm characteristics (9). Thus the confluence of more major tropical cyclones accompanied by higher storm surges and heavier rain with rising sea levels and increasing coastal populations translates to rapidly rising risks in coastal regions affected by tropical cyclones. In detailed studies in which changes in other storm characteristics, such as storm size and storm tracks, are accounted for, very substantial increases in damage are indicated (e.g., ref. 10).

Acknowledgments

I am supported by NSF through Grant NSF ICER-1854929.

- 1 Centre for Research on the Epidemiology of Disasters, (2016) EM-DAT: The International Disaster Database. <https://www.emdat.be/>. Accessed 1 May 2020.
- 2 J. P. Kossin, K. R. Knapp, T. L. Olander, C. S. Velden, Global increase in major tropical cyclone exceedance probability over the past four decades. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 11975–11980 (2020).
- 3 K. A. Emanuel, An air-sea interaction theory for tropical cyclones. Part I: Steady state maintenance. *J. Atmos. Sci.* **43**, 585–605 (1986).
- 4 K. Emanuel, The dependence of hurricane intensity on climate. *Nature* **326**, 483–485 (1987).
- 5 R. A. Pielke Jr et al., Normalized hurricane damage in the United States: 1900–2005. *Nat. Hazards Rev.* **9**, 29–42 (2008).
- 6 T. L. Olander, C. S. Velden, The advanced Dvorak technique (ADT) for estimating tropical cyclone intensity: Update and new capabilities. *Weather Forecast.* **34**, 905–922 (2019).
- 7 J. P. Kossin, T. L. Olander, K. R. Knapp, Trend analysis with a new global record of tropical cyclone intensity. *J. Clim.* **26**, 9960–9976 (2013).
- 8 K. A. Emanuel, A statistical analysis of tropical cyclone intensity. *Mon. Weather Rev.* **128**, 1139–1152 (2000).
- 9 N. Lin, K. Emanuel, M. Oppenheimer, E. Vanmarcke, Physically based assessment of hurricane surge threat under climate change. *Nat. Clim. Chang.* **2**, 462–467 (2012).
- 10 T. Houser et al., *American Climate Prospectus: Economic Risks in the United States* (Rhodium Group LLC, New York, NY, 2014).